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Evaluation of a Microwave Blade Tip Clearance Sensor for Propulsion Health Monitoring

Mark R. Woike

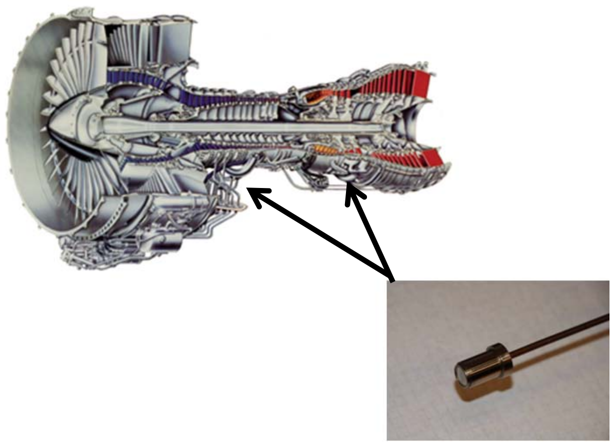
NASA Glenn Research Center

Outline

- Introduction
- Motivation
  - Aviation safety
  - Engine efficiency
- Experimental Approach
- Sensor Description
- Evaluation Testing
  - Calibration Rig
  - Large Axial Vane Fan
  - NASA Turbofan
  - Calibration & Spin Rig Tests
- Planned Vehicle Integrated Propulsion Tests
- Conclusion

Introduction

- Microwave Blade Tip Clearance Sensors
  - In-situ structural health monitoring for gas turbine engines
    - Blade tip clearance to monitor growth & wear
    - Blade Tip Timing to monitor deflection & vibration
  - Active closed loop clearance control
    - Closed loop control on turbine tip clearances



Microwave Blade Tip Clearance Sensor for Gas Turbine Engines

- Targeting use in the High Pressure Turbine (HPT) and High Pressure Compressor (HPC) sections
  - Survivability and operation in the high temperature environment has been a major issue
  - Microwave sensor technology has the potential to operate in this high temperature environment and fulfill this in-situ health measurement need

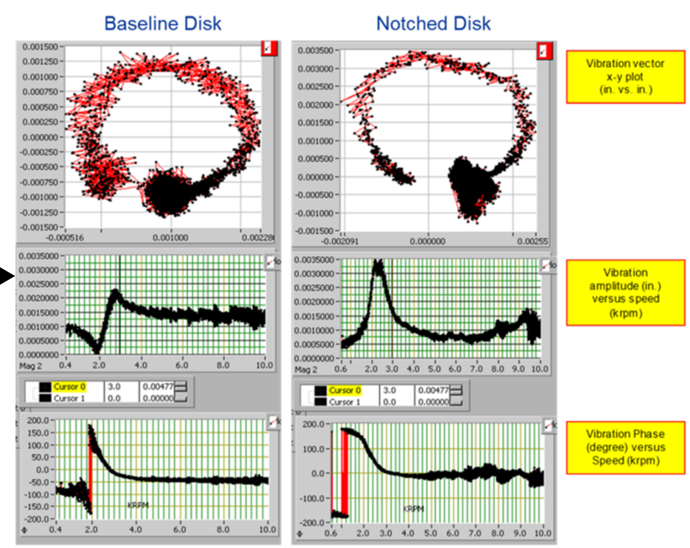
- ***Summarize previous efforts in evaluating this technology***
- ***Discuss future plans to evaluate technology on an engine ground test***

Motivation – Aviation Safety

- ***Enhance & improve aviation safety***
- NASA Aviation Safety Program (AvSP), Vehicle Safety Systems Technology Project (VSST)
  - Develop new instrumentation and techniques
  - ***Detect pre-cursors to events in order to take action and prevent failure***

Turbine Disk Failure – June 2, 2006

Crack Detection Experiments in GRC Rotordynamics Lab



Crack Detection Experiment Results

Motivation – Aviation Safety

- FAA Report AR-08/24 “Engine Damage Related Propulsion System Malfunctions”
- Damage in the HPT and HPC sections
  - **~32%** of damage events that caused engine removal for unscheduled maintenance
  - **~12%** of “in flight shut down” events

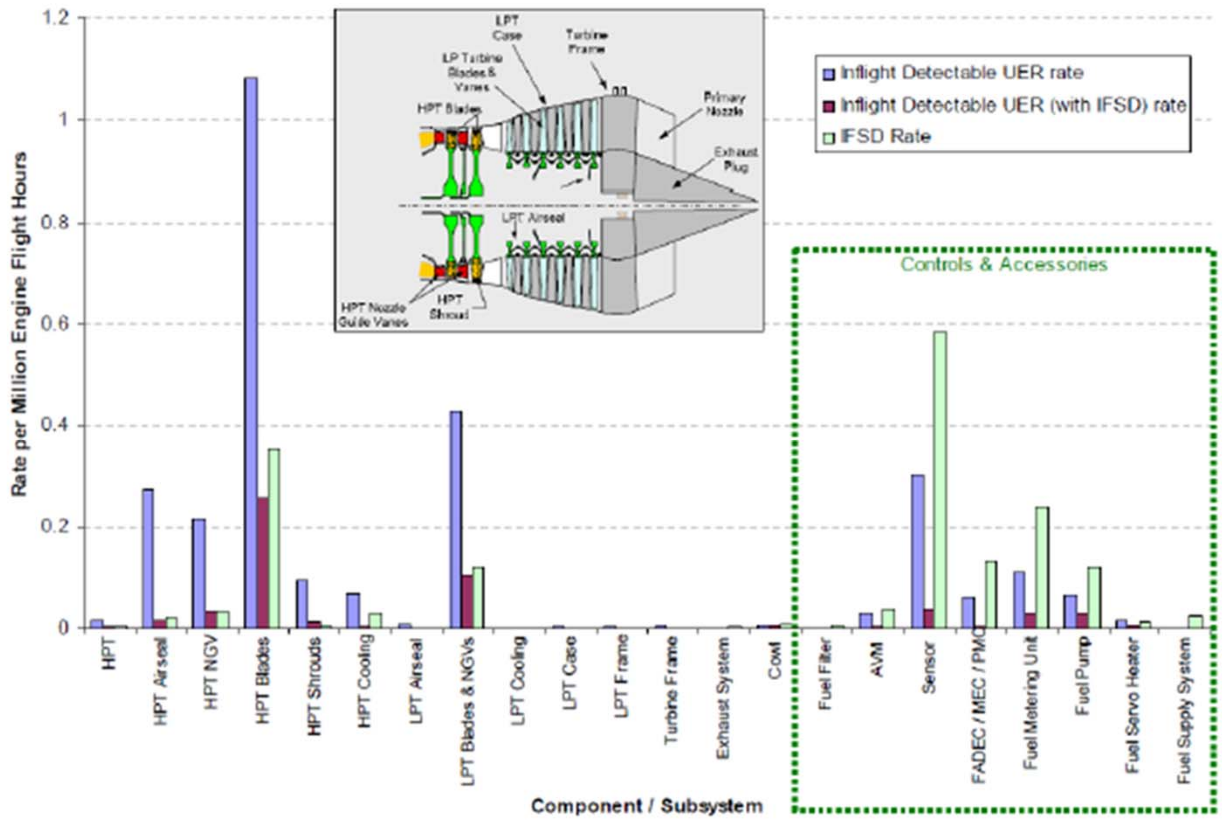


Figure 3-5. Engine Component Rates for Restrict Thrust Response Category (Continued)

Steve Clark, Grace Balut Ostrom, and Sam Clark, Engine Damage-Related Propulsion System Malfunctions, DOT/FAA/AR-08/24, December 2008.

Motivation – Engine Efficiency

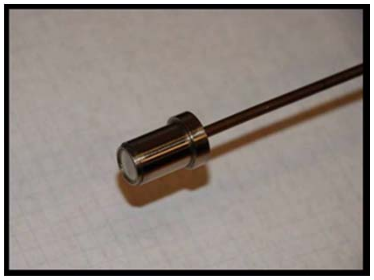
- ***Secondary goal (or primary depending on point of view!)***
  - Improve overall engine efficiency
  - Was being pursued under the NASA Fundamental Aero Program's, Supersonic Cruise Efficiency Project

- Active Closed Loop Clearance Control in the HPT*
  - It is estimated for every ~25um (~0.001)" decrease
    - SFC decreases ~0.1%
    - EGT decreases ~2 deg. F
  - Fuel savings
  - Reduced emissions
  - Extended service life

- ***Sensor "buys" its way onto the airplane for Structural Health Monitoring***

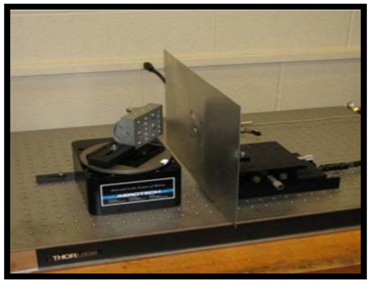
**** Lattime, S.B., and Steinetz, B.M., "Turbine Engine Clearance Control Systems: Current Practices and Future Directions," NASA TM 2002-211794, AIAA-2002-3790, 2002.***

Evaluation Approach 2006 to Now



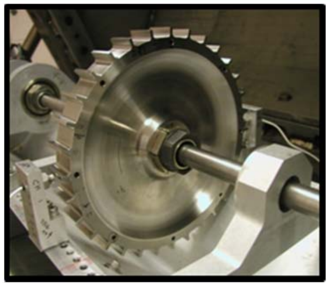
Microwave Clearance Sensor

Sensor Evaluation on High Pressure Burner Rig



Sensor Calibration

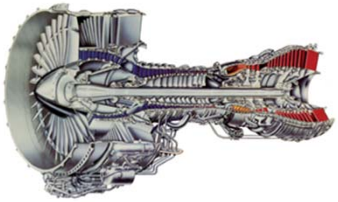
Clearance Evaluation on Large Axial Vane Fan



Rotordynamics & Fault Detection in Lab Testing

- Microwave tip clearance sensors and measurement developed by **Radatec, Inc (<u>now Meggitt</u>)** through the NASA Small Business Innovation Research (SBIR) Program and other commercial contracts
  - Phase III SBIR commercialization contract 2006-2007
  - First generation (5.8GHZ) production probes delivered in 2008
  - Second generation (24GHZ) probes delivered in 2009
- The use of microwave sensors for making tip clearance and tip deflection measurements is an emerging technology
  - Techniques on their use and calibration need to be developed
  - The sensor's overall accuracy and ability to make clearance measurements need to evaluated
- Several evaluation experiments were accomplished from 2006 to now as a means of building toward primary goal of using these sensors on an actual engine

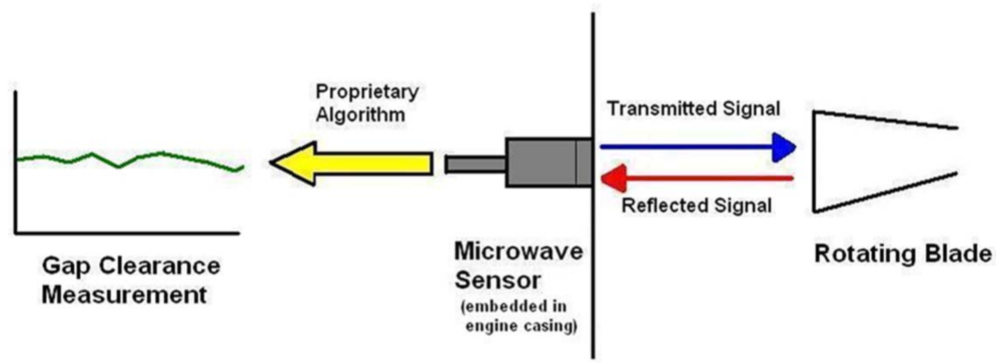
Clearance & Timing Evaluation on NASA Turbofan



Future Engine Ground Test

Sensor Description

- Probe is both a transmitting and receiving antenna
- The sensor sends a continuous microwave signal towards a target and measures the reflected signal
- The motion of the blade phase modulates the reflected signal
- The phase difference of the reflected signal is directly proportional to the distance between the sensor and the target

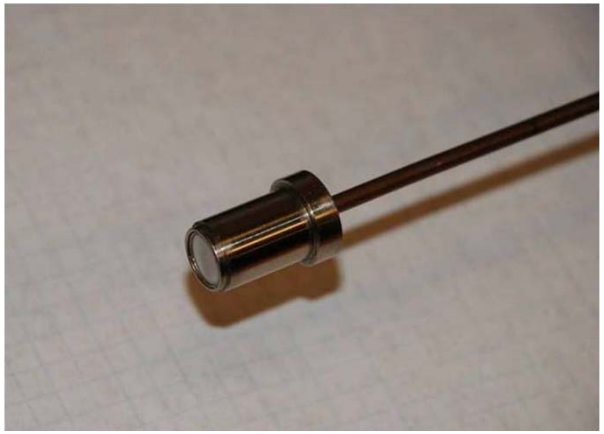


- Microwave blade tip clearance sensor performance goals (aero engine applications):

Measurement Range:	Accuracy:	Temperature:	Response:
Up to ~6 mm (~0.250 inches)	~0.025 mm (~ 0.001 inch)	~900ºC (~1600ºF)	> 1 MHZ (5 MHZ typical, in theory up to 25 MHZ possible)

Sensor Description

- Microwave Blade Tip Clearance Probe
  - First generation probes (5.8 GHZ)
    - For "large" rotating machinery
    - Measurement range ~25mm (~1")
  - Second generation probes (24 GHZ)
    - For aero engine size hardware and clearances
    - Measurement range ~6mm (~1/4")



Microwave Tip Clearance Probe

- Sensor Electronics
  - Contains the microwave generator and detector
  - Data acquisition & display computer
  - Located off board of test article or engine
  - Connected to sensors via co-axial cable

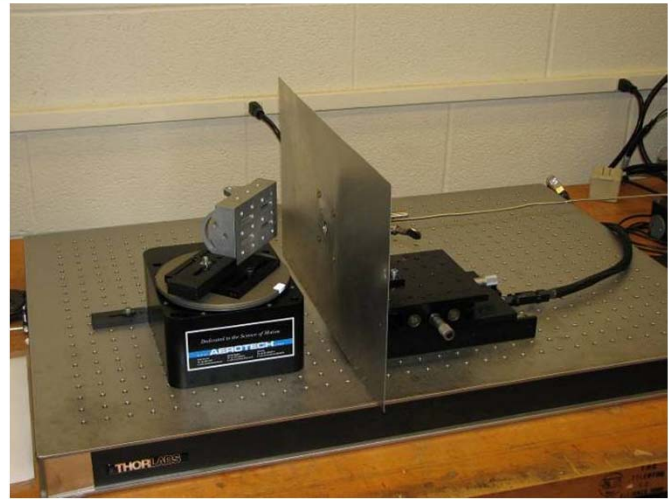
Microwave Sensor Electronics

Calibration Experiment (FY08)

- Objectives:
  - To develop calibration techniques
  - To evaluate 5.8GHZ probe's accuracy
    - Specific to the blade geometry
    - Average measurement of the geometry that is within the spot size caste on the blade
    - Need to map this "average" reading to the actual minimum clearance

- Calibrated the microwave sensors against two geometries
  - Over a range from 1 mm to 13 mm (.04" to .51")
  - "Thin" compressor blade (~6 mm thick)
  - "Thick" simulated fan blade (~26mm thick)

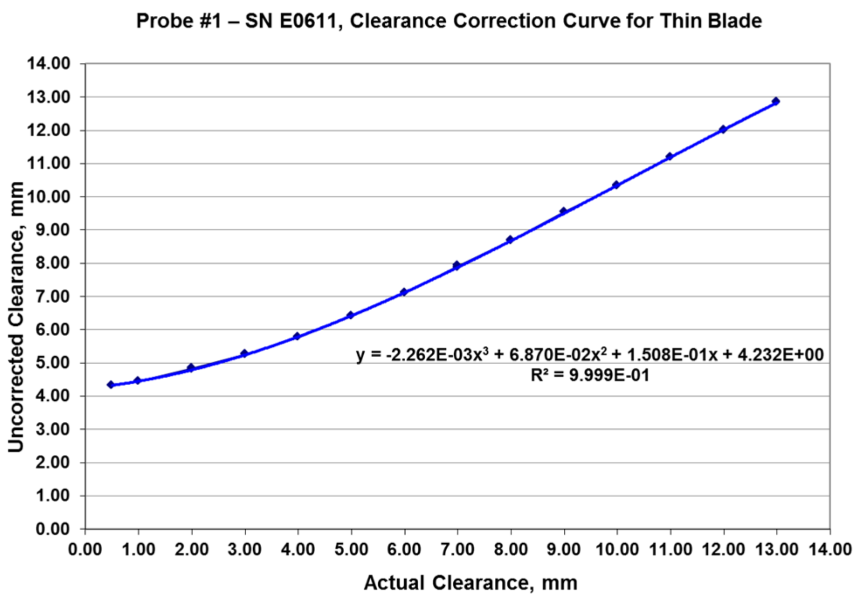
- Outcome / Results:
  - Developed techniques and infrastructure required for calibration
  - Observed worst case error of ***~+/- 0.17mm (~0.007")*** during this initial experiment (on thin blade)
  - Reduced to ***~+/- 0.05mm (~0.002")*** in subsequent calibration experiments for use on NASA Turbofan

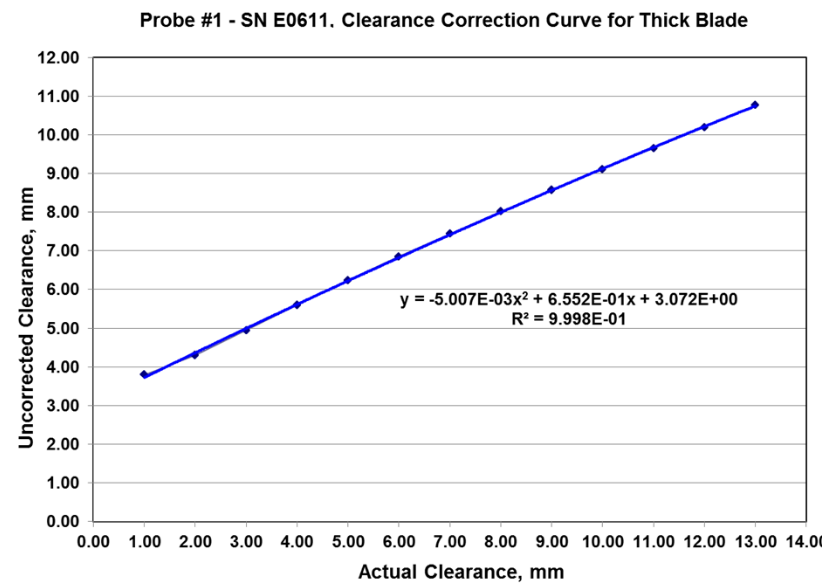


Probe Calibration Rig

"Thin" Compressor Blade

Results – Calibration Experiment (FY08)



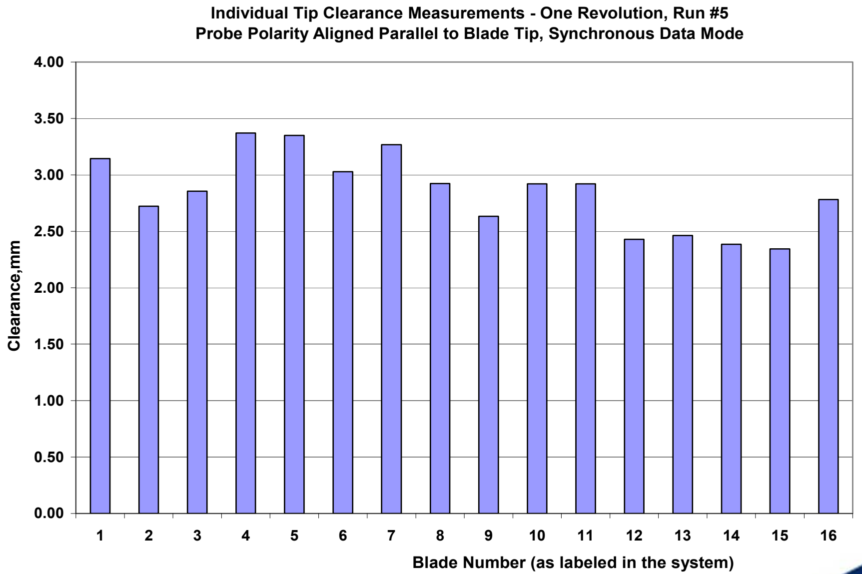


- Same sensor calibrated against two different geometries

Axial Vane Fan Experiment (FY08)

- Objectives:
  - Use the microwave sensor to make clearance measurements on actual rotating machinery
  - Evaluate how well the calibrations accomplished in the laboratory transfer into an actual use in the field
- Axial Van Fan
  - 1.8 M Diameter, operates at 1200 RPM
  - 16 Blades, ~26 mm thick (~1”) ,~362 mm (~14”) long, ~267 (~10.5”) mm chord length
  - One 5.8GHZ probe installed
- Outcome / Results:
  - NASA’s first use of these sensors on actual rotating machinery
  - Measured clearances were consistent with known operation of fan
  - Calibrations done in the lab against a simulated geometry appeared to transfer well into actual use in the field
  - ***Qualitative test to gain experience w/ sensors***

Axial Vane Fan at the Glenn Research Center’s 10x10 Wind Tunnel

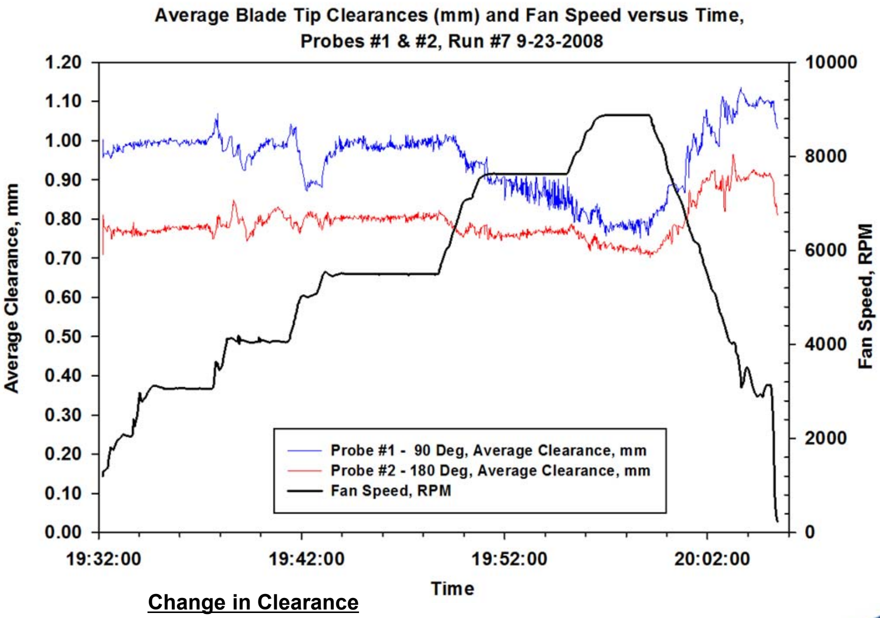


Axial Vane Fan – Blade Tip Clearances for 1/Rev

NASA Turbofan Experiment (FY08/FY09)

- Objectives:
  - Demonstrate the microwave sensors ability to acquire blade tip clearance measurements on an aero engine size test article and blades
- NASA Turbofan:
  - Subscale turbofan propulsion simulator
  - 2 probes (5.8GHZ) installed, 90º apart
  - 18 Composite Blades
    - Blade tips were coated with nickel to allow measurement by microwave probes
- Outcome / Results:
  - Acquired tip clearance data for several test runs of the turbofan
  - ***The change in tip clearances measured during fan operation was in-line with previous data acquired with capacitive probes on earlier test entries***
  - ***Demonstrated the sensor's ability to make measurements on "aero" engine size hardware***

NASA Turbofan at the Glenn Research Center's 9x15 Wind Tunnel

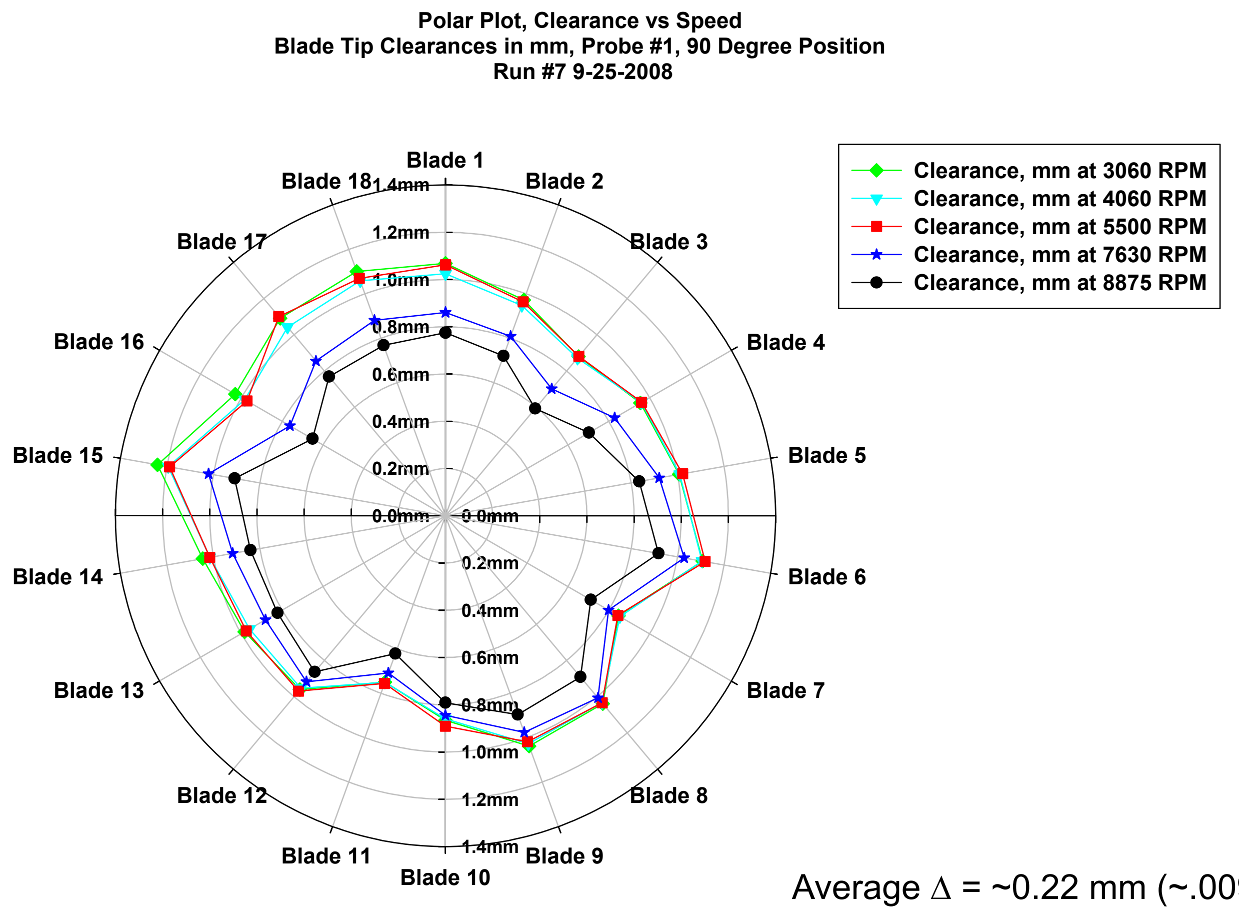


Change in Clearance

Probe #1 Δ = 0.22 mm (~.009")

Probe #2 Δ = 0.06 mm (~.002")

Results - NASA Turbofan Experiment (FY08/FY09)



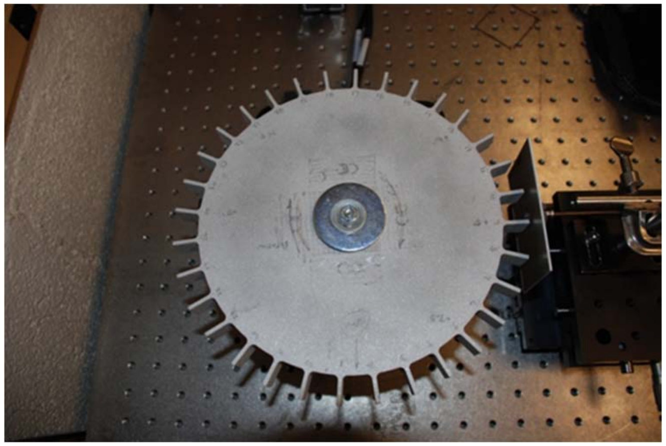
Average ∆ = ~0.22 mm (~.009")

Spin Rig Tests (FY10-FY12)

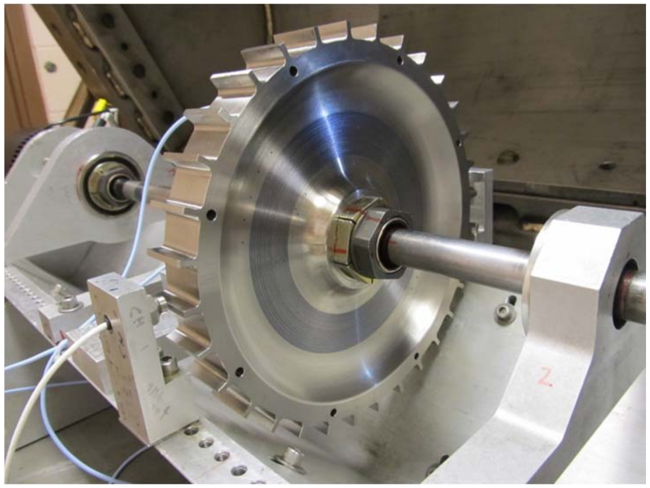
- Objectives:
  - Evaluate second generation (24 GHZ) sensor's ability to make ***low range clearance measurements and deflection measurements***
  - Evaluate their use in sensor based fault & crack detection schemes that are being developed to monitor rotor structural health

- Tested on several engine like disks on GRC's Calibration Rig and the High Precision Spin Rig
  - Disk with blades pre-bent at specified angles for tip deflection evaluation
  - Several disk with notches introduced to simulate cracks

- Results:
  - Operated at clearances down to 0.10mm (.004")
    - Evaluation range: 0.10mm to 0.60mm (.004" to .024")
  - Investigated ability to make deflection measurements
  - Sensor successfully used to monitor blade tip clearance in several crack detection experiments accomplished in our Rotordynamics Laboratory

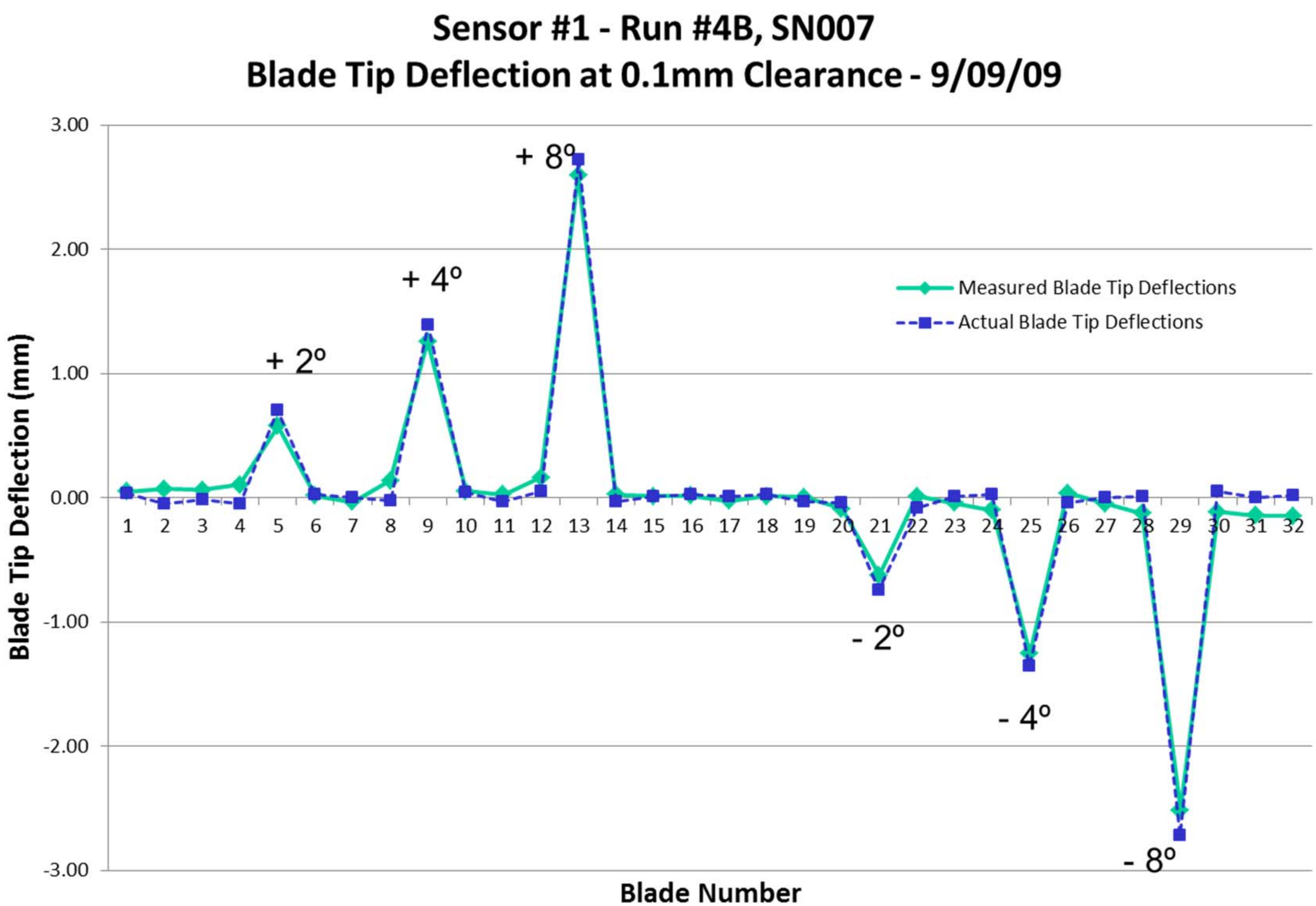


Blade tip clearance and timing testing on the sensor Calibration Rig



NASA GRC High Precision Spin Rig
Microwave sensor being used for the development of a vibration based crack detection technique

Spin Rig Tests (FY10-FY12)



Vehicle Integrated Propulsion Research (VIPR) Overview

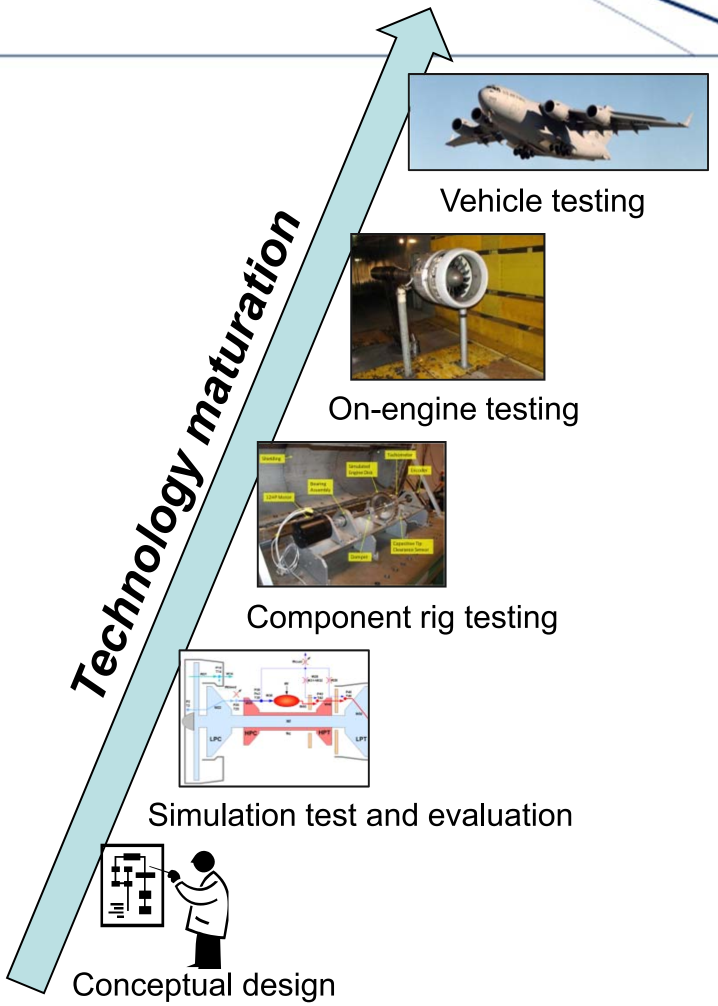
VIPR test approach:

- A series of on-wing engine ground tests
- Technologies under evaluation include advanced EHM sensors and algorithms
- Includes "nominal" and "faulted" engine operating scenarios

Partnerships:

- Sharing of costs, results and benefits
- VIPR partners include NASA, other government agencies and industry partners.

VIPR Test Schedule

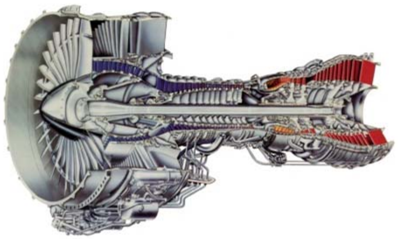


Testing is a necessary and challenging component of Engine Health Management (EHM) technology development.

VIPR I Test Overview

- VIPR I test was conducted in December 2011 at NASA Dryden / Edwards Air Force Base
- Test vehicle:
  - Boeing C-17 Globemaster III
  - Equipped with Pratt & Whitney F117 turbofan engines
- VIPR 1 EHM ground tests included:
  - A series of nominal and faulted engine test cases
  - Data collected over a range of power settings including quasi-steady-state and transient operating conditions

Boeing C-17 Globemaster III



Pratt & Whitney F117 Turbofan Engine

Results & Future Plans

- VIPR 1 (2011) - Microwave blade timing / tip clearance sensor
  - Not installed on engine, close as possible for EMI/EMC checkout
  - Successfully passed electro-magnetic interference (EMI) / electro-magnetic compatibility (EMC) checkout.
  - Cleared for actual on-engine use for future VIPR tests at DFRC.

- VIPR 2 (2013) & 3 (2014) Plans
  - Install microwave blade tip clearance sensors on engine in HPT section.
    - Goal of evaluating for EHM and closed loop clearance control
  - Other Advanced sensors will be installed.
  - Evaluate additional EHM sensors and algorithms under nominal and faulted engine operating scenarios
  - Initial steps towards EHM sensor fusion with advanced sensor suite.
  - Run engine to end of life.

Conclusion

- Testing to date has shown that microwave tip clearance sensor technology has proven successful in acquiring blade tip clearance measurements on rotating machinery and other “aero engine” like hardware
  - Demonstrated the techniques and infrastructure required for probe calibration
  - Used 5.8 GHZ sensors to make measurements on an Axial Vane Fan and a NASA Turbofan
  - Used 24GHZ sensors to make measurements on smaller aero engine like hardware in various test rigs
- Demonstrate in an actual turbine engine environment
  – Full scale test with a suite of EHM sensors being targeted for 2013-2014